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TITLE LINEAR NONADIABATIC PULSATIONS OF HOMOGENEOUS ZAMS STARS

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LINEAR NONADIABATIC PULSATIONS OF HOMOGENEOUS ZAMS STARS

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ABSTRACT.

Current uncertainty about the most massive observed stars has led to a reexamination of the most massive star that is stable against radial pulsation. The nuclear energy generation equations in the LNA linear, nonadiabatic code have been considerably improved, so that it is now appropriate to redo the study to determine the maximum mass of a ZAMS star that will be stable against pulsation.

INTRODUCTION.

The question of the most massive star continues to motivate astronomers. The existence of very luminous O3 supergiants, Hubble-Sandage variables, and Wolf-Rayet stars have motivated evolutionary calculations in the mass range above 60 $M_\odot$. The inclusion of mass loss, both steady and in strong episodic bursts in evolutionary calculations, has made it possible to construct an evolutionary stellar sequence from main sequence to H-S variables to Wolf-Rayet stars to supernovae.

Theoretical efforts have historically focussed on pulsational stability (Ledoux, 1941; Schwarzschild and Harm, 1959; Aizenman, Hanson, and Ross, 1975) which suggested a lower limit of 60$M_\odot$ for stellar pulsation. The epsilon mechanism which depends on a strong temperature dependence of the CNO cycle of nuclear reactions, was shown to be capable of driving stable radial stellar pulsations for masses above 60 $M_\odot$. It was supposed that these pulsations would grow to sufficient amplitude that the star would either disintegrate or by mass loss approach a more stable mass range. In 1970-1971 (Appenzeller 1970, 1970a; Simon and Stothar 1970; Ziebarth 1970; Talbot 1971) proposed through nonlinear calculations that (1) the amplitudes of surface zones might be small even though strong pulsational driving occurred in the core or (2) that shock waves would develop damping further amplitude growth and causing enhanced mass loss. Such limitations were thought to lift the domain of stability to about 100$M_\odot$. Ziebarth, as a result of extensive LNA modelling, summarized the composition dependence of the critical mass for stable pulsations by the formula:

$$M_C = 100(1.0 + 4.19Z - 0.83Y) \pm 2.0\ M_\odot.$$

Davidson (Humphreys and Davidson, 1983) has searched unsuccessfully for photometric variations in promising O3 stars in Carina which may support this hypothesis.

explaining observations of H - S variables and Wolf-Rayet stars, in the mass range above 100 Mo. Thus the question of pulsational stability has been raised again and a recent preprint by Klapp, Langer and Fricke (1986) (herein after KLF) reexamines this issue. A linear non-adiabatic (LNA) analysis of homogeneous zero-age main sequence (ZAMS) stars with chemical composition (Y,Z) = (.277, .043) yields the surprising result that stars below 400 $M_{\odot}$ were pulsationally stable against radial pulsations.

Because of the challenge raised by the unusual results of KLF and the increased sophistication of the nuclear energy generation programs, the authors decided to redo the classical Ledoux- Schwarzschild-Harm calculations and those of the early 1970s to redetermine the critical mass for pulsational instability.

RESULTS.

In order to make a successful model of a star in which pulsational driving comes from the epsilon mechanism, it is obviously very important to have the best possible nuclear energy generation program, including details of the chemical and temperature dependence. The current program in the Los Alamos LNA code includes the Iben energy generation terms as well as the Fowler et al. (1975) reaction rates. The calculations covered (1) the mass range 70 to 160 $M_{\odot}$ at Z = 0.015 and (2) the composition range in $0.005 < Z < 0.043$ for X = 0.689 and a mass of 130$M_{\odot}$. The dependence of the period, P_o, and growth rate, P_o/T_o, where T_o is the e-folding time, on mass for fixed composition are shown in Table I. It will be seen that the periods form a generally increasing sequence with mass, while the growth rates are much more erratic, as shown in Fig. 1. Nonetheless, the growth rates become positive between 80 and 90$M_{\odot}$ which is in agreement with the earlier results. In an accompanying article in this issue, O'Dell, Pauserwein, Weiss, and Hajek also obtain similar results. The variation with Z is in Table II.

Table I.

Results of Fundamental Mode Radial Pulsation for Z = 0.015 and Y = 0.296. For comparison the average life of a 60 to 160 $M_{\odot}$ star is about 3 x 10^6 years.

Mass $M_{\odot}$	log $L/L_{\odot}$	log T_{eff}	Period hours	P_o/T_o	T_o years
70	5.857	4.702	9.17	-2.944E-7	1,640
80	5.960	4.712	7.51	-2.356E-8	36,300
90	6.045	4.722	7.98	5.355E-7	1,700
100	6.123	4.728	8.30	3.330E-7	28,400
110	6.189	4.734	8.89	9.807E-7	1,030
120	6.252	4.737	9.30	1.030E-6	1,030
130	6.304	4.746	9.17	6.394E-7	1,640
140	6.353	4.750	9.17	5.090E-7	2,050
160	6.443	4.752	10.61	2.125E-6	570

Radial pulsation calculations for $130M_\odot$ as a function of Z with X = 0.689 and 0.8Z=CNO

Z	log $L/L_\odot$	log T_{eff}	Period hours	$P_\odot/T_\odot$	$T_\odot$ years
.005	6.309	4.760	8.73	1.312E-6	5,681
.010	6.252	4.737	9.30	1.030E-6	6,858
.015	6.304	4.746	9.17	6.396E-7	11,200
.020	6.303	4.739	9.51	9.037E-7	7,642
.030	6.299	4.730	8.73	1.312E-6	5,738
.043	6.293	4.716	10.31	2.397E-7	26,594

For comparison, the results of KLF for composition (X,Z) = (.687, .043) give $P_\odot$ = 9.43 hours, a growth rate of - 5.511E-7, and an e-folding time of 1,954 years. KLF maintain that not until about $440M_\odot$ does a positive growth rate occur for pulsation in the fundamental mode. The run of growth rates with Z is also shown in Fig. 1. The result of KLF is also shown. The variation of growth rate with Z is fairly unambiguous. We did not go to a low enough Z to replace CNO entirely with p-p burning, so that our results do not apply to Population III stars.

The nature of the driving for the pulsation is shown in Fig. 2, which records the PdV work per zone for each of the 359 zones. It will be seen that the driving takes place in the first 55 zones at temperatures above 29 million degrees and damping thereafter. It is believed that the erratic driving at approximately one million degrees is due to discontinuities in the opacity fit.

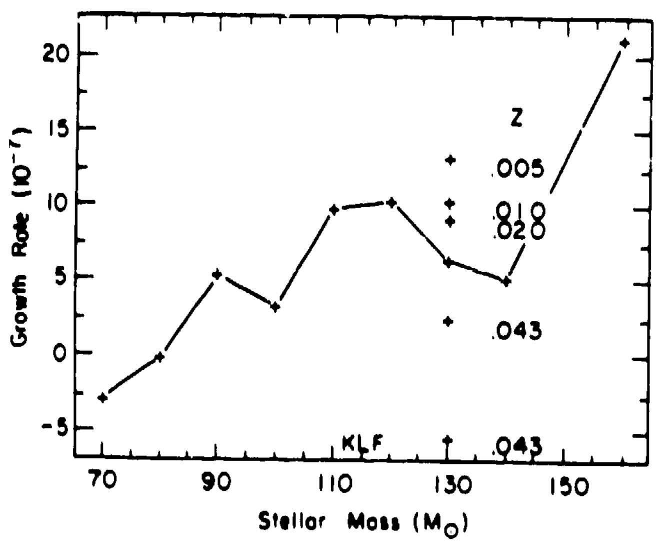

Fig. 1

Growth rates as a function of mass for Z = .015 and for various Z at $130M_\odot$.

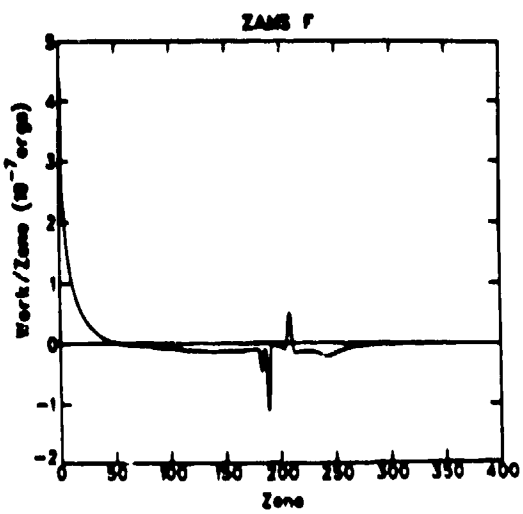

Fig. 2

Work per zone for the $120M_\odot$ case.

The location of the critical mass for pulsation for massive stars has been redetermined to be very close to 80 $M_{\odot}$. The location on the HR diagram of a number of homogeneous ZAMS stars have been determined using the Los Alamos LNA program in good agreement with current evolutionary results. J. Cahn thanks S. Starrfield for formatting and printing this paper.

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